Marine Geology 386 (2017) 88–97

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

Longshore sediment transport and foreshore change in the swash zone of an estuarine beach

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ARTICLE INFO

Article history:
Received 17 September 2016
Received in revised form 25 February 2017
Accepted 28 February 2017
Available online 3 March 2017

Keywords:
Beach erosion
Longshore current
Microtidal beach
Sediment transport
Fetch constraints

ABSTRACT

Estuarine beaches often lack well developed surf zones; incident waves break and convert directly to swash on the steep foreshore, resulting in greater influence of the swash zone in generating longshore flows and sediment transport. This study was conducted to evaluate longshore sediment transport in the swash zone of an eroding estuarine beach and relate transport rates to changes in beach position and volume downdrift of a shore-perpendicular structure. Field data were gathered on a sandy beach on the bay side of Fire Island, New York, USA in a short fetch (12–15 km) microtidal (mean range 0.21 m) environment. Wave and swash processes, beach changes and sediment tracer and trapping experiments were conducted during strong onshore winds in March and April 2012.

Daily topographic surveys of the beach revealed pulses of sediment movement alongshore at small temporal (daily) and spatial (5 m) scales. The mid foreshore retreated 2.75 m from the beginning to the end of the 24 days of monitoring. This retreat was associated with a loss of 2.1 m^3 of sediment per meter of shoreline length. The greatest amount of foreshore retreat during a single storm event was 1.27 m, associated with a volume loss of 0.9 m^3 of sediment per meter. Mean wind speed on that day was 11.3 $m\ s^{-1}$ with a maximum of 18.2 $m\ s^{-1}$; significant offshore wave height at the time of maximum wind speed was 0.30 m. Mean significant wave heights ranged from 0.12 to 0.26 m during the five times when trapping occurred, resulting in mean longshore swash velocities of 0.08 to 0.23 $m\ s^{-1}$ and transport rates ranging from 0.413 to 1.516 $m^3\ h^{-1}$. The longshore sediment transport rates are similar to rates gathered under similar longshore current velocities on microtidal low energy beaches. Transport rates on beaches in sheltered environments can differ from rates calculated using existing formulas that may be more appropriate for high-energy beaches, where a greater proportion of sediment is transported in the surf zone than in the energetic swash zone under plunging breakers. Transport rates calculated from three existing formulae (Bagnold, 1963, CERC, 1984, Kamphuis, 2002) revealed that estimates from Bagnold compared most favorably with measured rates because of direct measurements of longshore current velocities. Rates of erosion on beaches in short fetch environments can be high despite low wave energies because the low, narrow beaches have little volume, magnifying the importance of seemingly low rates of transport in the swash.

1. Introduction

The swash zone is defined as the part of the beach alternatively covered and exposed by wave uprush and backwash, which corresponds to the beach face - the relatively steep part of the beach extending seaward from the berm to low tide level (Masselink and Puleo, 2006). Reviews of swash processes (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006; Bakhtyar et al., 2009) point to the significant contribution of swash to sediment transport and therefore to shoreline accretion and erosion, while also noting the difficulties of monitoring sediment transport in the swash zone in the field. These difficulties occur because of the frequently reversing flow directions onshore and offshore that make it difficult to deploy sediment traps and the intermittent wetting and drying of the beach that confound attempts to measure fluid flows. Despite these difficulties, collection and analysis of field data is needed for development of swash-zone sediment transport models (Butt and Russell, 2000). Information on longshore flows and resulting sediment transport is especially needed (Elfrink and Baldock, 2002; Masselink and Puleo, 2006; Austin et al., 2011). Field data on longshore transport is lacking for low energy beaches (Schoonees and Theron,

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http://dx.doi.org/10.1016/j.margeo.2017.02.017

1993), where much of the longshore transport takes place in the swash (Lampe et al., 2003; Nordstrom et al., 2003).

This study was conducted to evaluate longshore sediment transport in the swash zone of an eroding estuarine beach and relate transport to changes in beach volume and position. We identify the potential for transport in the swash zone versus the surf zone of estuarine beaches, which is related to the influence of beach morphology on wave approach and wave breaking. The data are used to identify the applicability of existing sediment transport formulae (Inman and Bagnold, 1963, CERC, 1984, Kamphuis, 2002) to identify their applicability to estuarine beaches. We also underscore how rates of transport are related to rates of erosion, where longshore obstructions restrict delivery of sediment from updrift.

Previous studies note a fundamental difference between relatively high-energy dissipative beaches where infragravity energy plays a major role in swash flows and reflective beaches where swash flows are forced by incident waves (Hughes et al., 2014). Wave energy on estuarine beaches is dominated by incident frequencies, and swash flows are driven by wave breaking on the beach face. Estuarine waves are locally generated and their height, period and direction of approach are dependent on wind direction and speed and fetch distance (Nordstrom, 1992; Freire et al., 2007). The direction of wave-induced longshore currents usually corresponds to the direction of wind approach in fetch-limited environments due to the effects of both wind-generated waves and wind shear (Sherman and Greenwood, 1985; Davidson-Arnott and McDonald, 1989).

Most studies of longshore sediment transport have been conducted on exposed beaches with well-developed and gently sloping surf zones, making results difficult to apply to estuarine beaches. Sediment transport on estuarine beaches with steep foreshores and low gradient low tide terraces is concentrated right on the intertidal foreshore within the breaker and swash zones. Factors such as breaker type, mixing depths, turbulence intensity and the lack of a surf zone may play a role in differences (Bodge and Kraus, 1991; Wang and Kraus, 1999; Smith et al., 2009). For example, mixing depths are greater on the steep foreshores of estuarine beaches than in the surf zone of flatter beaches for a given wave height (Kraus, 1985; Sherman et al., 1994; Ciavola et al., 1997). The greater mixing depths result in volumetric transport values from tracer experiments that are almost twice the values derived using empirically-based mixing depth equations for more exposed beaches (i.e. Kraus, 1985). Bodge and Kraus (1991) suggest the relative intensity of longshore sediment transport increases with the Iribarren number (ratio of foreshore slope to wave steepness), and limited field data from low-wave energy environments suggest this may be important in accounting for the difference in transport rates (Ciavola et al., 1997; Nordstrom et al., 2003; Tonk and Masselink, 2005) where sediment suspension by breaking waves can be the dominant process in upper foreshore erosion (Shi et al., 2013).

Estuarine beaches are often characterized by a broad, flat low tide terrace and a steeper upper foreshore separated by a pronounced break in slope near mean low water (Nordstrom, 1992; Eliot et al., 2006; Freire et al., 2007, 2009). Wave energy is dissipated as low spilling waves on the low tide terrace during low water levels. Waves can pass over the low tide terrace without breaking at high water levels and break on the beach as plunging waves, with conversion directly to swash. As a result, the volume of sediment moved in the swash zone can greatly exceed the volume moved on the low tide terrace. Previous studies in the lab and field, have found relative increases in longshore sediment transport in the swash zone (Van Wellen et al., 2000; Smith et al., 2009). Bodge and Dean (1987) found that the amount of sediment moved in the swash increased dramatically as wave breaking changed from dissipative breakers to collapsing breakers with a stronger contribution by wave-induced mass transport. A previous comparison of trapping rates across the swash and surf zones of a beach in a short fetch environment revealed that rates in the turbulent breaker and swash zone can be 7–14 times greater than bayward of the breakers (Lampe et al., 2003). Swash zone transport appears to contribute relatively more to the total longshore transport rate in lower energy environments (Smith et al., 2009).

Erosion and accretion on estuarine beaches can be manifested in retreat and advance of the foreshore with little change in profile shape (Jackson et al., 2005). Changes in beach volume are a function of the longshore current and are altered by shore-perpendicular obstacles, such as peat outcrops, that function as traps to sediment moved alongshore. Change in profile shape caused by erosion on the upper foreshore and deposition on the lower foreshore is usually associated with strong winds blowing more directly onshore. Change in profile shape need not result in volume loss across the profile. Longshore volume loss, in contrast, can displace the shoreline landward. The longshore component of the swash thus appears to play an important role in determining erosion rates on estuarine beaches.

Our study was conducted at Sailors Haven on the bay side of Fire Island, New York, USA (Fig. 1). The data were gathered in association with a study of the fate of beach fill emplaced in November 2011. The long-term geomorphic changes associated with transport of sediment from the fill were evaluated in a previous study using semi-annual beach profiles surveyed at 5-m intervals alongshore over a distance of 160 m from 2011 to 2013 (Nordstrom et al., 2016). This study makes use of pressure transducers, current meters, dyed sand tracers, sand traps and microtopographic measurements gathered in a 28 day field deployment to relate sediment transport rates and directions and changes in beach volume to simultaneous measurements of waves and currents. This study builds on Nordstrom et al. (2003) by providing direct measurement of longshore current velocities in the swash zone, determining rates of transport and rates of erosion, comparing rates to transport formulae and refining the explanation for sediment transport on estuarine beaches.

2. Study area

The field site (Fig. 2) is west of a wooden sheet pile bulkhead that projects about 115 m into Great South Bay. The presence of the bulkhead provides the opportunity to evaluate the significance of longshore transport where its geomorphic effect is enhanced by a shore perpendicular structure that acts as a control on sediment input to the beach. Throughput of sediment on a long beach without an obstruction would be less likely to reveal sediment pulses passing a specific location. The shoreline west of the marina (Fig. 3) is characterized by segments of eroding *Phragmites australis* marsh separated by eroding woodlands. Fetch distances for wave generation are 12 km to the northwest and 15 km to the northeast. Mean tidal range is 0.21 m; spring tidal range is 0.24 m. The active foreshore varies from 7 to 9 m in width, with a slope 5 to 6°. The slope of the inner low tide terrace is 0.4 to 0.5° near the foreshore and extends offshore for hundreds of meters. Water depths in the bay are often <1.5 m within 1 km of the shoreline. The shallow offshore limits wave heights under strong onshore winds. A field study conducted several hundred meters west of this site in 1992 provided insight to sediment mixing depths, longshore transport rates using tracers, and relationships between waves, winds and beach profile changes (Jackson et al., 1993; Sherman et al., 1994; Nordstrom et al., 2003).

A total of 1747 m^3 of beach fill was emplaced in November 2011. Analysis of five bulk sediment samples taken from the foreshore before fill emplacement and five taken one month after emplacement revealed that all were moderately well sorted medium sand (Nordstrom et al., 2016). This field study was conducted from 11 March to 7 April 2012, after winter storms had reworked the fill into a configuration representative of an active estuarine beach, with foreshore width, grain size and slope similar to the nearby non-nourished beach(Fig. 3). Wave energies are high at this time of year, the ground is not frozen, and the beaches are relatively free of the wrack accumulations that can interfere with instruments.